Optical Fiber Technology xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Optical Fiber Technology

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Regular Articles

Design of a bending-insensitive single-mode photonic crystal fiber

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ARTICLE INFO

Article history:
Received 19 September 2012
Revised 14 January 2013
Available online xxxx

Keywords:
Bending-insensitive
Single-mode
Photonic crystal fiber (PCF)

ABSTRACT

We present a design of a bending-insensitive single-mode photonic crystal fiber (PCF) based on the existence of a triangular core formed by three neighboring air holes missing in the center of the fiber, and two cladding layers of air holes with different diameters. By optimizing the design parameters, the designed PCF with bending-insensitive characteristics can match the requirements of fiber to the home applications very well. Simulation results show that the designed PCF has an effectively single-mode operation, a small bending loss below 0.15 dB/m for the bending radius of 5 mm, as well as a stable effective mode area of 80 μm^2 whatever the designed PCF is straight or bent, which can connect well with conventional single-mode fibers (SMFs).

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1. Introduction

Along with the development of Fiber To The Home (FTTH), the bending-insensitive optical fiber, which operates under small bending radius, has been a major focus of enterprises for research recently [1]. Although the standard single-mode fiber (SMF) has been able to meet some needs of the central office, the outdoor cable box, and the building backbone network on dense and flexible wiring, the minimum radius for the SMF to be bent is approximately 30 mm. Therefore a large bending loss will generate when the bending radius is less than 30 mm. It cannot be met the applications in FTTH. A designed fiber with a cone-shaped index in core [2] performs better bend-compensated performance than the standard design, but it is a multi-mode fiber, which still cannot meet the FTTH requirements.

Photonic crystal fibers (PCFs) have attracted much attention and been investigated widely in recent ten years as a new class of optical fibers [3]. It is composed of a single medium with some micro air holes, whose size and arrangement can be arbitrary adjustable. Because of their flexible designs and special structures, PCFs can easily realize some useful and unique properties unlike traditional optical fibers, such as endlessly single-mode (ESM) transmission [4], large mode area (LMA) [5], high birefringence [6] and other unique properties in optical communication and other applications [7].

Bending characteristics of PCFs have been investigated theoretically as well as experimentally in some papers [8–11], including the bending-induced mode distortion and the bending loss. Kim et al. observed that the bending characteristics of total internal reflection-PCF with a large hole-to-hole pitch experimentally in 2003 [9]. They found that the spectral loss of that PCF is sensitive to micro- and macro-bending. When the bending radius decreases to a few centimeters, the transmission loss will increase rapidly with bending radius decreasing. In 2004, Nielsen et al. [10] demonstrated an expression for the prediction of the macro-bending loss for LMA–PCFs with a triangular air-hole lattice. The predicted edge of the bending loss for a typical LMA–PCF is in accordance with the measured value.

Up to now, various designs of PCFs with some unique bending properties have been deeply and thoroughly studied for different practical applications [12–14]. For example, a design of a PCF with an extremely LMA [13] and low bending loss was reported in 2005, which can be used in compact high power laser systems. In 2011, Azizur Rahman et al. [12] put forward a new design by bending a highly birefringent PCF for single-mode single-polarization operation, which is potentially used in sensing applications. Tsuchida et al. reported a design of a PCF with a doped core surrounded by two air-hole rings [15], to achieve an effective mode field area (MFA, A_{eff}) of ~68 μm^2 at 1550 nm. The PCF has a lower bending loss of 0.35 dB/m for a bending radius of 5 mm.

In this paper, we propose a new structure of a PCF with a great ability to resist the bend for FTTH applications, and carry out a detailed investigation on bending characteristics of the PCF. The designed PCF is composed of a triangular core formed by three neighboring air-holes missing in the center of the fiber, and two cladding layers of air holes with different diameters of d_1 and d_2. By appropriately adjusting the design parameters, the designed PCF has a cutoff wavelength below 1.064 μm, a stable A_{eff} of 80 μm^2, whatever the fiber is straight or bent, and a small bending loss of 0.15 dB/m at 1550 nm for a bending radius of 5 mm, which is a particular improvement over previous PCF designs.

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http://dx.doi.org/10.1016/j.yofte.2013.01.004

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2. Principle and theoretical analysis

The fiber is designed to be a bending-insensitive optical fiber with an effectively single-mode operation. Fig. 1 shows the topology cross section of the designed PCF. The well developed optical fiber is actually a modification from a conventional PCF, which retains its internal geometry along its entire length. The core is formed by three neighboring air holes missing in the center of the fiber, which is nearly a triangular shape. The cladding of the fiber is composed of two types of air holes with different diameters. d_2 is the diameter of the large air holes, d_1 ($d_1 < d_2$) is the diameter of small air holes, respectively, and Λ is the hole pitch. The function of the ratios between Λ and air-hole diameters (d_1, d_2) is to maintain an effectively single-mode operation of the designed PCF with a lower confinement loss of the fundamental mode (FM) and a higher confinement loss of the higher order modes (HOMs). [4,16] To improve the bending-resistant ability of the designed PCF, we design a special refractive index profile of the PCF to diminish the expected bending-induced equivalent index gradient by increasing the diameter of air-holes around the core. In this paper, we consider the operating wavelength of 1550 nm in order to properly understand the bending properties of the designed PCF, and the cutoff wavelength is defined numerically such as the confinement loss of the FM less than 0.01 dB/m and the confinement loss of the HOMs more than 5 dB/m at 1064 nm to maintain an effectively single-mode operation over the optical transmission windows from 1250 nm to 1625 nm.

Applying the commercial software COMSOL MULTIPHYSICS [17], we use the full-vector finite-element method (FEM) with an anisotropic perfectly matches layer (PML) [18] to simulate the characteristics of this designed PCF structure. The silica refractive index is assumed to be 1.45 for calculation, and the air refractive index is considered as $n = 1$.

As a transmission medium, optical fiber is inevitable to be bent in practical applications. When the PCF is bent, the bending-induced mode distortion diffuses outward in the direction of the bend and the bending loss occurs. To study the effects of the bend, we apply the conformal transformation method [19] to convert a bended PCF to its equivalent straight PCF with a modified index profile. The equivalent modified index distribution, n_{eff} (x, y) [20] can be given in the x plane as follows:

$$n_{eff}(x,y) = n(x,y)\left(1 + \frac{x}{R_{bend}}\right) \tag{1}$$

where $n(x, y)$ is the original refractive index profile of the PCF, R_{bend} is bending radius, and x is the distance from the center of the PCF. Due to the bend, the equivalent refractive index of the cladding outside will be lower than the equivalent index of the inside cladding. Therefore, the FM shifts farther outward to the cladding with the confinement loss increasing.

Meanwhile, when the PCF is bent, it will simultaneously generate the bend-induced mode distortion, which has an important direct impact on the mode area as well as losses. This distortion can substantially reduce effective mode area and increase the bending losses. Therefore, the bend-induced MFA and the bending loss of the designed PCF must be taken into account in the fiber design. Based on the analysis of the mode distribution and the effective refractive index, the A_{eff} of the PCF is obtained from [21]:

$$A_{eff} = \frac{\left(\iint_S |E_t|^2 dx\,dy\right)^2}{\iint_S |E_t|^4 dx\,dy} \tag{2}$$

where E_t denotes the electric field vectors and S is the whole cross section of the PCF. According to a well-known formula, the bending loss L_b can be defined as [22]:

$$L_b = \frac{2 \times \pi \times 8.686 \times I_m(n_{eff})}{\lambda} \tag{3}$$

where n_{eff} is the wavelength dependent effective index, $I_m(n_{eff})$ is coefficient of the imaginary part of n_{eff}, and λ is the wavelength, respectively.

3. Numerical results

Fig. 2 shows the mode field distributions of FM of the designed PCF with d_1 of 1.375 μm, d_1/Λ of 0.229, and d_2/d_1 of 2.91 at the state of straight and bent with the bending radius of 5 mm, respectively, where the operating wavelength is at 1550 nm. When the designed PCF keeps straight, the light is well confined to the core and no energy leaks into the cladding as can be seen from Fig. 2a. The mode field distribution of FM is Gaussian-liked, which can be seen from Fig. 3. The intensity distributions of FM along x- and y-axis are shown in Fig. 3a and b, where the blue and black curves correspond to the modes with the parameters with $d_2/d_1 = 2.91$ and 3.13, respectively. The red lines are Gaussian fitting curves, and there almost entirely coincide with the curves of the mode intensity distributions of the designed PCF along

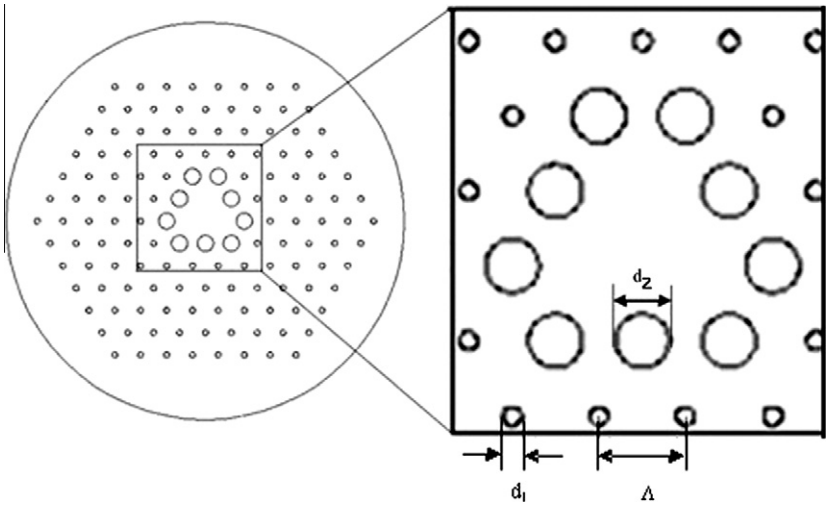

Fig. 1. Schematic cross section of the proposed PCF with a triangular core and two cladding layers. The air-hole diameter of the inner ring is d_1, and the rest air-hole diameter of the outer rings is d_2.

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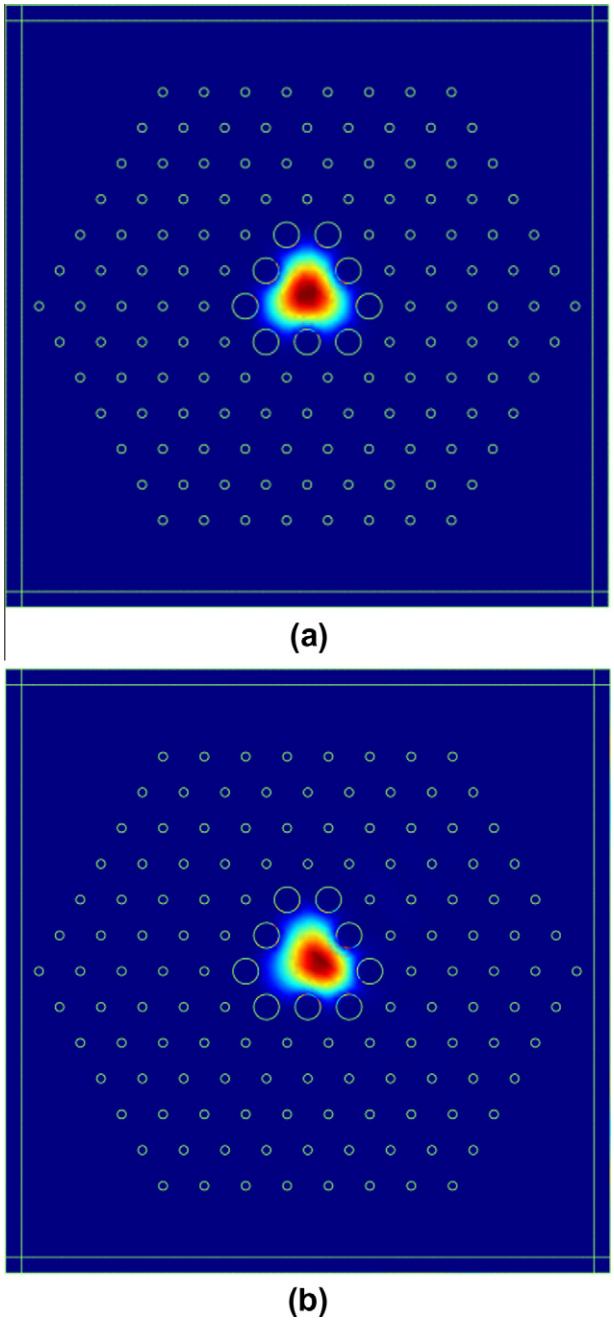

Fig. 2. The mode field distributions of the PCF at 1.55 μm of the designed PCF with d_1 of 1.375 μm, d_1/Λ of 0.229, and d_2/d_1 of 2.91 (a) no bend and (b) the bend radius of 5 mm.

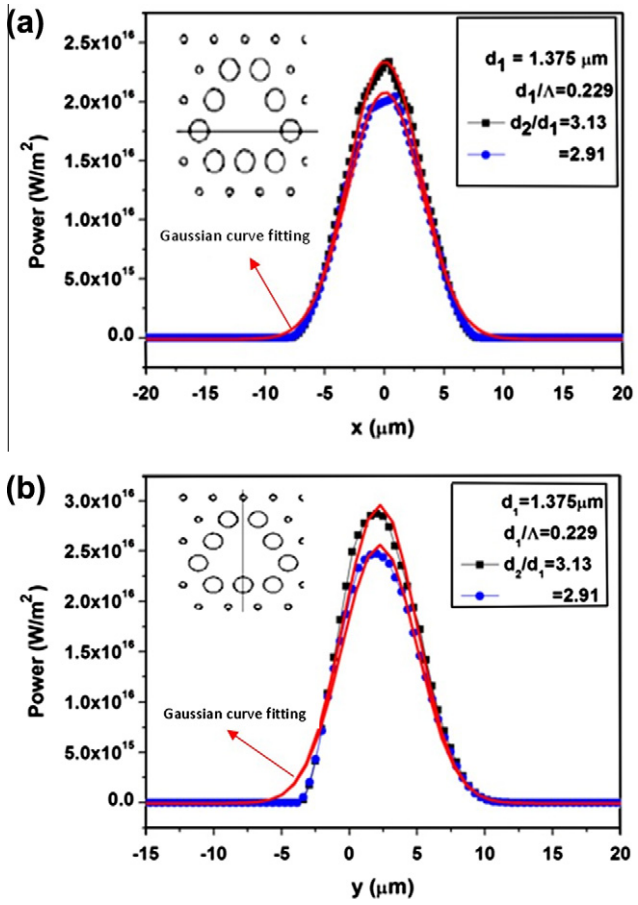

Fig. 3. The distributions of the mode intensities along (a) *x*- and (b) *y*-axis in the designed PCFs; the red lines are the fitting curves for Gaussian beams. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

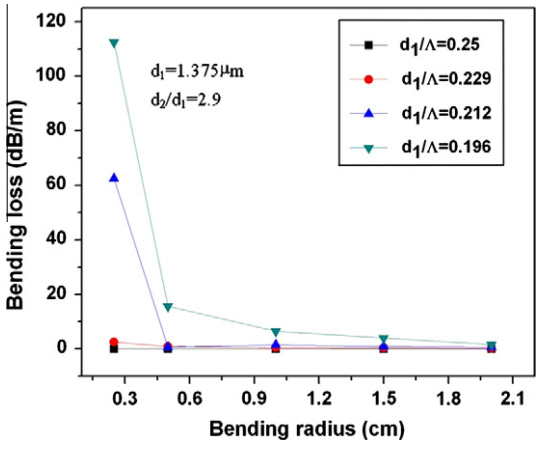

Fig. 4. The theoretical dependence of the bending loss with the bending radius for different pitches Λ but with a fixed d_1 of 1.375 μm and d_2/d_1 of 2.9. The wavelength is 1550 nm.

x- and *y*-axis. That means the splicing loss between the designed PCF and the conventional SMF can be low. For small bending radius of 5 mm, the mode field distribution of the FM becomes compressed to one side of the triangular core as can be seen from Fig. 2b, but most of light energy is still transmitting in the core with no leakage diffusing to the cladding.

In order to optimize the bending characteristics of the designed PCF, simulation analysis is discussed for the impact of the parameters on bending characteristics of the designed PCF. Fig. 4 shows the theoretical dependence of the bending loss with the bending radius for different pitches Λ, but with a fixed d_1 of 1.375 μm and d_2/d_1 of 2.9. Numerical simulations show that the bending loss is strongly dependent with the bending radius for a small value of d_1/Λ, while it keeps low in a wide range of bending radius for a large value of d_1/Λ. When the value of d_1/Λ is less than 0.229, the bending losses of the designed PCF increase dramatically with the bending radius decreasing. But the losses are relatively flat for a large value of d_1/Λ (more than 0.229). For example, the bending loss of the model with d_1/Λ of 0.196 is 1.69 dB/m with the bending radius R_{bend} = 2 cm, but when the bending radius decreases to 2.5 mm, the loss reaches 112.4 dB/m. In contrast,

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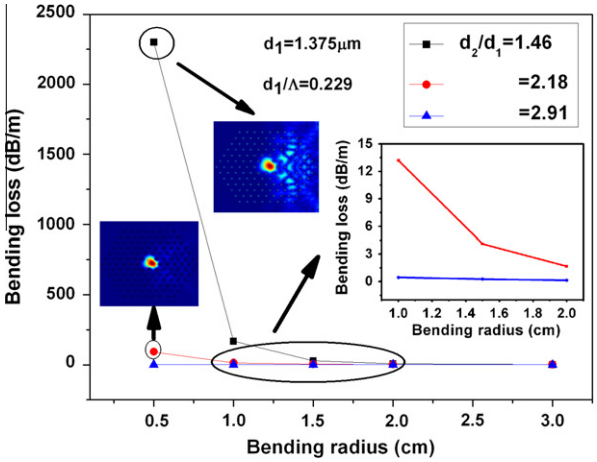

Fig. 5. The dependence of the bending loss with the bending radius for the designed PCF with the air hole diameter d_1 of 1.375 μm and a fixed d_1/Λ of 0.229, but different d_2/d_1.

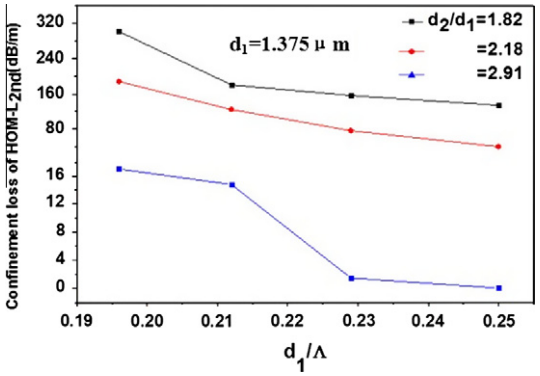

Fig. 6. Confinement loss of the HOM-L^{2nd} as a function of the various values of parameters Λ and d_2, with a fixed d_1 of 1.375 μm, where the operating wavelength is 1.064 μm.

the bending loss of the model with d_1/Λ of 0.25 is only changing from 0.0176 dB/m to 0.044 dB/m when the bending radius varies from 2 cm to 2.5 mm. That is because a strong light confinement of an optical fiber brings up a good bending-resistant ability. Therefore, by increasing the value of d_1/Λ with a fixed value of d_2 ($d_2 > d_1$) and Λ, the bending-insensitivity of the designed PCF can be improved.

Fig. 5 shows the dependence of the bending loss with the bending radius for the designed PCF with d_1 of 1.375 μm and a fixed d_1/Λ of 0.229, but for different d_2/d_1. We can clearly observe that the bending loss of the designed PCF is also strongly dependent on the bending radius, when the value of d_2/d_1 is less than 2.91, whilst it is relatively flat with a low value for a large value of d_2/d_1 (more than 2.91). The loss is less than 0.35 dB/m over the range of the bending radius from 3 cm to 1 cm, when the ratio of d_2/d_1 is 2.91. The calculated FM field distribution of the designed fibers with $d_2/d_1 = 1.46$ and 2.18 are presented in the insets of Fig. 5, respectively, where the bending radius is 5 mm. No doubt that changing the value of d_2/d_1 can improve the bending-insensitivity of the designed PCF. Therefore, by introducing a ring of air-holes with a larger diameter around the core, the bending-insensitive characteristic of the designed PCF can be greatly optimized. According to the above analysis, both decreasing the air-hole pitch Λ and increasing the diameters of d_2 can improve the bending characteristics of the designed PCF.

In order to maintain an effectively single-mode operation of the designed PCF, Fig. 6 shows the confinement losses of the second-order mode (HOM-L^{2nd}) at 1064 nm as a function of d_1/Λ for various d_2, but with a fixed value of d_1 of 1.375 μm. (The confinement loss of the FM is always less than 0.01 dB/m for any parameters we used.) As shown in Fig. 6, the confinement loss of the HOM-L^{2nd} is strongly dependent on the value of d_1/Λ. It decreases as the value of d_1/Λ increases. For example, when d_2/d_1 is 2.91, the confinement loss of the model with d_1/Λ of 0.196 is 17.3 dB/m, but that is less than 0.02 dB/m for the model with $d_1/\Lambda = 0.25$ as can be seen from the blue[1] line in the figure. One can also note that the changing of d_2/d_1 can strongly influences the confinement loss. We can easily obtain a higher loss of the HOM-L^{2nd} by increasing the pitch. Therefore, by keeping only the parameter d_1 constant and varying the values of d_2 and Λ to ensure that the HOMs with large confinement losses suffer very large propagation loss while the FM remains guided with very low loss, we can obtain an effectively single mode operation of the designed PCF.

The A_{eff} is another important parameter for the fiber, which affects the input power, nonlinear effect, the splicing loss with other fibers, and so on. Fig. 7 shows the A_{eff} of the designed PCF with a fixed d_1, but different parameters of d_2 and Λ. It is obvious that the A_{eff} compresses with the values of d_2/d_1 and d_1/Λ increasing since the refractive index difference between the core and the cladding decreases. For a good bending-insensitive PCF with d_1/Λ of 0.25 and d_2/d_1 of 2.91, the bend loss is 0.052 dB/m with $R_{bend} = 5$ mm, but the A_{eff} of that PCF is only 52.3 μm^2, which is too small for some practical applications. Meanwhile, the confinement loss of the HOM-L^{2nd} is less than 0.03 dB/m, which cannot maintain an effectively single mode operation of the designed PCF.

According to our simulations and calculations above, we choose an optimal structure of the designed PCF with d_1 of 1.375 μm, d_2/d_1 of 3.13 and d_1/Λ of 0.212 to analyze the bending performance in detail. The confinement loss of the FM is less than 0.01 dB/m, whereas that of the HOM-L^{2nd} reaches to 5.35 dB/m at the wavelength of 1.064 μm. So the designed PCF can maintain an effectively single mode operation over the optical transmission windows. Theoretical simulations also reveal that the designed PCF is not only bending-insensitive, but also has a suitable effective A_{eff} of ~80 μm^2, whatever the designed PCF is straight or bent. The distributions of the mode intensities along x- and y-axis in this designed PCF are also Gaussian-liked as shown in Fig. 3.

Fig. 8 shows the bending loss of the designed PCF as a function of the bending radius at the wavelength of 1550 nm. The bending loss curve of the x-polarization mode is as similar as that of the y-polarization mode. The bending loss variations of both the x- and y-polarization modes are relatively flat with a value below 0.22 dB/m, when the bending radius is larger than 4.5 mm. When the bending radius is less than 4.5 mm, the bending losses are rising dramatically with the bending radius decreasing. For the bending radius of 5 mm, the bending loss of the y-polarization mode is only ~0.145 dB/m, which is better than that of Ref. [17]. It means that the designed PCF can works well for a small bending radius of 5 mm.

Fig. 9 shows the effective A_{eff} of the designed PCF as a function of the bending radius at the wavelength of 1550 nm. The A_{eff} is almost a constant when the bending radius is larger than 10 mm. When the radius decreases continuously, the A_{eff} of the designed PCF drops just a little. The A_{eff} is ~79.32 μm^2, ~76.6 μm^2, and ~74.9 μm^2 at the bending radius of 10 mm, 5 mm, and 4.5 mm, respectively. The changing of their mode field distributions is shown in the insets for the bending radius of 40 mm, 10 mm, and 4.5 mm, respectively. It means that the designed PCF has a good ability to mitigate the bending-induced mode distortion.

[1] For interpretation of color in Fig. 6, the reader is referred to the web version of this article.

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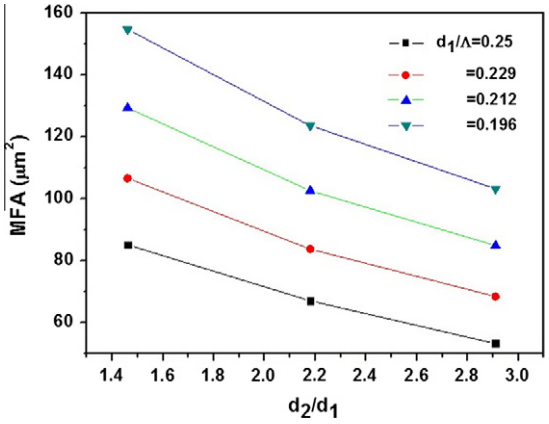

Fig. 7. The MFA of the PCFs with different pitch and d_2. d_1 is 1.375 μm.

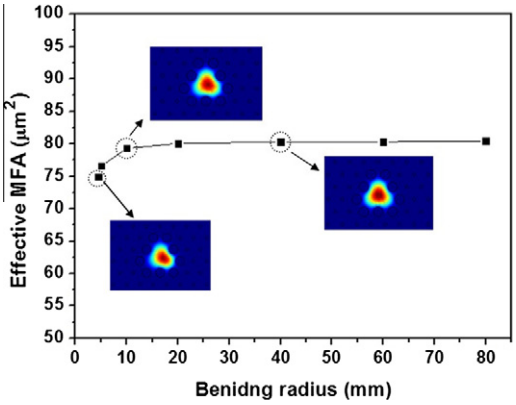

Fig. 9. The bend-induced effective mode area of the *x*-polarization mode of the designed PCF.

Table 1
Comparison of the optimized designed PCF parameters and the fiber parameters reported in Ref. [15] for the bending radius R_{bend} = 5 mm and a wavelength λ = 1550 nm.

	The designed PCF	Fiber from Ref. [5]
Cutoff wavelength (μm)	⩾1.064	⩾1.1
MFA in straight fiber (μm²)	~80	~68
MFA in bent fiber (μm²)	~76.6	–
Bending loss (dB/m)	0.15	0.35

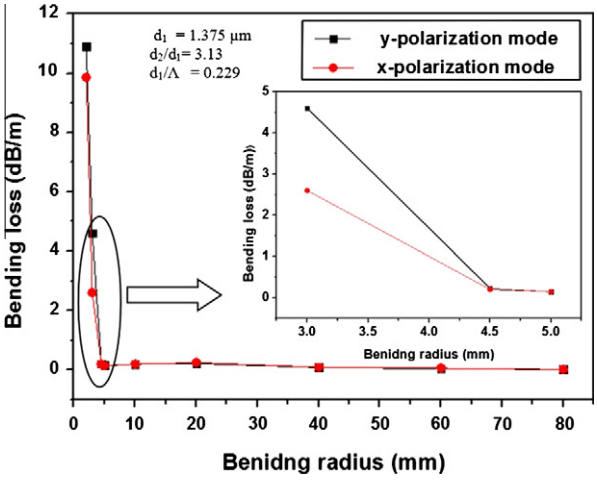

Fig. 8. The bending loss of the *x*- and *y*-polarization modes of the designed PCF as a function of the bending radius.

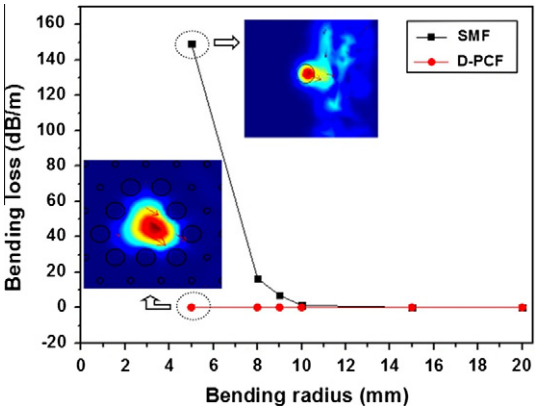

Fig. 10. The bending loss of the *x*-polarization mode of the designed PCF compared to the SMF depending on the bending radius. The near field distributions of the PCF and the SMF for a bending radius of 5 mm are shown in the insets.

Furthermore, to validate the bending characteristics of the designed PCF is greatly improved, we have made a comparison of the bending loss between the designed PCF and the SMF ($\Delta = (n_{core} - n_{cladding})/n_{core}$ = 0.004, core diameter d = 4.5 μm).

Fig. 10 shows the dependence of the bending loss on the bending radius for the designed PCF and the SMF, respectively, where the operating wavelength is 1550 nm. The bending property is improved effectively for the designed PCF. We can obviously see that the bending loss of the designed PCF is much lower than that of the SMF. For instance, the bending loss of the SMF increases largely when the bending radius is below 10 mm. While that of the designed PCF keeps small until the bending radius decreases to 5 mm. The bending loss of the SMF is ~149.35 dB/m at the bending radius of 5 mm, whereas that of the designed PCF is only 0.142 dB/m. The insets show the mode distributions of the designed PCF and the SMF at a bending radius of 5 mm. It is clear that the energy transmitting in the SMF leaks out when the fiber is bent, while that of the designed PCF does not change obviously. That is the reason for the designed PCF with a great ability to resist the bend. This bending property can meet the FTTH requirements well.

Compared with the PCF reported in Ref. [15], which is also designed for the FTTH network construction, the parameters of the optimized designed PCF are summarized in Table 1. We can clearly see that our designed PCF reveals larger MFA and lower bending loss than the PCF reported in Ref. [15]. In particularly, the MFA of our optimized PCF can effectively prevent the bend-induced MFA reduction. What's more, we consider the fabrication process for the PCF reported in Ref. [15] with a Germanium-doped core surrounded by two layers of air holes will be complicated. Our fiber designs can therefore be potentially suitable for the FTTH applications.

4. Conclusion

In conclusion, we present a bending-insensitive single-mode PCF. The triangular core and two cladding layers illustrate the advantages of the bending-insensitive PCF for transmission applications. The designed PCF has an effectively single-mode operate, a small bending loss below 0.15 dB/m for the bending radius of 5 mm at 1550 nm, as well as an stable A_{eff} of ~80 μm², whatever the designed PCF is straight or bent, which can match well with SMFs. The bending-insensitivity, the steady and suitable A_{eff} on

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bending radius is the main advantages of the designed PCF, which can have many potential applications.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant No. 61108058, the National Basic Research Program of China (973 Program) under Grant 2010CB327804.

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Please cite this article in press as: Z. Wang et al., Design of a bending-insensitive single-mode photonic crystal fiber, Opt. Fiber Technol. (2013), http://dx.doi.org/10.1016/j.yofte.2013.01.004